

Student Name Brad Jayakody

HET608

Student ID 7168837

Project Supervisor Tyler Bourke

SAO Project Cover Page

Project 29

Project Title Search for Other Worlds

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Introduction

In 1584, an Italian Philosopher by the name of Giordano Bruno, published the book "*De l'Infinito, Universo e Mondi*" in which he theorised that stars also had planets orbiting them, and that these planets could also host intelligent life (Fridlund 2010). Bruno was ahead of his time, and these, amongst other views, led to him being burned at the stake. Epicurus in around 300 BC and Demokritos around 400 BC were two philosophers who also wrote about the possibility of the existence of other planets outside the Solar System (Fridlund 2010). Planets that are located outside the Solar System are often given the name exoplanet, short for extrasolar planet. Although theories about the existence of exoplanets have existed for centuries, only recently technology has advanced far enough for them to be discovered. While searches have been conducted in depth since the 19th century, it was only in the late part of the 20th century, less than 20 years ago, that the first confirmed exoplanet was found (Wolszczan & Frail 1992) and in that relatively short period of time, over 500 exoplanet candidates have been discovered (ExtraSolarWeb). One of the goals of exoplanet searches is to find a planet that is capable of supporting life, and hopefully confirm that life exists elsewhere in the universe apart from Earth. Analysis of star systems with planets also helps understand how the Solar System was formed. This paper will discuss the primary methods of exoplanet searches, the various attributes of the planets found so far, give a brief history of the important exoplanet discoveries and discuss exoplanet search projects.

Search Methods

There are various different methods used in searching for exoplanets. Each method has had a different success rate and possesses various levels of complexity. Some methods can only detect exoplanets within tens of light years, while others can detect them on the very edges of the Milky Way. Each method also provides a different amount of knowledge about that planet and star system. By attempting to detect a planet with a different method once first discovered via an alternative method, we can improve the scope of information known about that planet, and also confirm the existence of that exoplanet via an alternate means.

Optical Images

One of the most difficult methods of discovering exoplanets is via optical imaging. Optical imaging is the analysis of images obtained by optical telescopes. The main problem of this method is that the visible light reflected by a planet, even a massive gas giant planet, such as Jupiter, is drowned out by the light emitted from the star it orbits. For example, on visible wavelengths Earth is about ten thousand million times fainter than the Sun, and Jupiter, a gas giant planet, is roughly a thousand million times fainter (Jones 2008). As we go up the light spectrum into infrared wavelengths, the effect is reduced. By taking the Solar System as a base example, even at infrared, Earth is a million times dimmer than the Sun and Jupiter still about 100,000 times dimmer (Jones 2008).

The relative dimness of planets would not be an issue if we could obtain an image at a high enough resolution, where the star and planets could be seen easily. However, there is a limit to how sharp we can make these images, even outside Earth's atmosphere. This limit is called the diffraction limit. Diffraction is where light waves spread out. A telescope with a large diameter will catch more of the light that the astronomical object outputs, therefore, the larger a telescope, the better the resolution. Furthermore, ground based telescopes have to overcome atmospheric effects and even

light pollution from Earth (Freedman & Kaufmann 2008). To combat atmospheric turbulence, astronomers use adaptive optics (Freedman & Kaufmann 2008). This is where a deformable mirror changes shape to improve the resolution. However in order for this method to work, the telescope needs to have a bright star within the telescope's field of view as a reference point.

Another method to improve resolution is interferometry. The principle behind interferometry is to take the results of at least two telescopes, preferably more, and to combine the images. Combining the images this way, can achieve telescope resolution that is the same as that of a telescope that is the size of the distance between the telescopes (Freedman & Kaufmann 2008).

A space based interferometer would provide good results at detecting planets, and due to being able to study the infrared band in detail outside Earth's atmosphere, it might even be able to detect evidence of life on exoplanets. One such project that is currently in the early days of testing and planning is the Terrestrial Planet Finder-Interferometer (TPF-I) by NASA (TPFIWeb). This project, as well as other similar projects are discussed in more detail later in this paper under the "Future Searches" section.

While a planet may be difficult to detect, one part of a planetary system that can more readily be discovered by optical methods is the debris disc. The debris disc is a disc of matter that the planets were formed from. It consists of the remnants of planet formation and contains smaller objects, like meteors and comets (Jones 2008). While the evidence of a disc does not prove the existence of a planet, it can be considered as evidence that planets could have formed in the system. The disc is more easily detectable as it covers a much larger area, thus the light from the star can't drown out the disc. More than 1,000 stars have been found to have a debris disc (Jones 2008), so while this isn't direct evidence, it is a good indication that other methods can be employed to analyse the star system for exoplanet evidence.

One advantage of searching via optical means is that images taken previously by telescopes can be studied at a later date to search for evidence of exoplanets which allows the search for exoplanets via optical imaging to piggyback on other projects.

Stellar Photometry

Stellar photometry is the study of the brightness of a star and its changes over time. The results of photometry can provide indirect evidence to deduce that a planet exists. The two methods that rely on stellar photometry are transit photometry and gravitational microlensing.

Transit Photometry

If the orbit of a planet around a star results in the planet passing between our vantage point and the star, we can observe that the visible radiation from the star is reduced as the planet obscures part of the star (TransitWeb). This dimming will be extremely small, and can only be observed at certain times during the planet's orbit. A planet with a short orbital period will be easier to detect than a planet with a long orbit, as the longer orbit will require more time spent observing the star. The planet will have to be sufficiently large, at least a Jupiter sized gas giant planet, in order to block out enough of the star's radiation (Irwin 2008). By observing the decrease in the brightness of the star, we can also calculate the radius of the planet itself by using the radius of the star and the simple ratio of Brightness of Planet/Brightness of the star (Jones 2008). Analysing when the star becomes

less bright, and the period when this happens, we can calculate the orbital period of the exoplanet, and via an estimate of the star's mass, the orbital semi-major axis can also be obtained (Jones 2008).

Furthermore, the planet's temperature can be determined, as the difference in infrared radiation can be measured when the planet passes behind the star. Combining this with the radius of the planet, an estimate can be made as to the temperature of the planet (Jones 2008). This information is useful when seeking to find a planet that could support life, based on our current understanding of what is needed for life to flourish.

While the above makes it sound fairly simple, there is a major assumption that all of the star's surface is the same brightness, which it is not. Depending on the orientation of the star, and the path of the orbit as viewed from Earth, the decrease in brightness could be greater or smaller (Jones 2008). Another issue is that instead of a planet passing between us and the star, another less bright star could be passing between us and the observed star, as in a binary system, although it has been discovered that the light curves differ in these cases (Jones 2008). Hence any discovery needs to be checked to ensure it has not been contaminated by bodies other than a planet.

Taking the Solar System as an example, if Jupiter was observed in transit, the change in brightness would be about 1% (Jones 2008). This would be easily detectable. While Earth, on the other hand, would be around 0.008% (Jones 2008), which would be much harder to detect, and impossible from within the Earth's atmosphere.

Another indirect approach that can be used is by studying the orbital period of a giant planet. If the period is accurately mapped down to a few seconds, by studying any fluctuations in the period, this could suggest the existence of another Earth-sized planet tugging at the larger planet (Jones 2008).

Gravitational Microlensing

According to Einstein's theory of general relativity, light will bend as it passes through an area of strong gravity (Freedman & Kaufmann 2008). A distant background star will send out its light, and as it approaches the star we wish to observe, the light will bend around it. The star will cause an increase in the apparent brightness of the distant star. As the planet then passes between our observation point and the distant star, the brightness will again increase (Freedman & Kaufmann 2008). The downside of this method is that the planet must orbit the star at a far enough distance in order to observe the change in brightness, and the planet's orbit must also be on the correct plane for our observation (Bennett 2008). One of the main benefits of this method is the fact that it can detect planets tens of thousands of light years away, the furthest of any method, and also around less bright stars where other methods would not detect the planet. Furthermore, this method also detects lower mass planets, down to $0.1M_{\oplus}$ (Bennett 2008). Planets can also be detected even before the star has been discovered, or if the star is unseen. If the mass of the star is also known, the mass of the planet can be calculated. Finally, planets with a very long orbital period can be detected much faster compared to the other methods, however we do not learn much about the planet's orbit itself.

Motion of Stars

The vast majority of the discoveries of exoplanets have been made by observing how the planets affect the motion of the star they orbit. Most exoplanets have been discovered via Doppler spectroscopy or the radial velocity method as it is also known.

Astrometry

Stars are not stationary in space, they are moving through space. If they have either a companion star, or a planetary system they will not move in a straight line (Jones 2008). If there is a planet orbiting the star, the star will orbit around the centre of mass in the system. The centre of mass, which is a point which normally does not contain any matter, will be travelling in a straight line (AstrometryWeb), thus the star will slightly orbit around the centre of mass. Thus, by measuring the star's orbit around the centre of mass, we can determine the orbital period of the planet and the mass of the planet. Astrometry has been used as a technique for searching for exoplanets since at least 1938, by Peter van de Kamp at Swarthmore College's Sproul Observatory (Boss 2009), but it has had a controversial history. This method failed to produce any results in over 50 years, which led some scientists to denounce the method, but finally VB 10b, located in the constellation Aquila, was the first planet to be detected by astrometry in 2009 (VB10bWeb). However, due to more accurate telescopes, such as ALMA (Atacama Large Millimetre Array) currently in development and discussed later in this paper under "Future Searches", this method may prove to be more successful in the future. While the theory behind astrometry was sound, until recently the technology had not evolved to a point where it could be used to achieve good results.

Doppler Spectroscopy/Radial Velocity

More exoplanets have been discovered by Doppler spectroscopy(also known as the radial velocity method) than all the other methods combined (ExtraSolarWeb). Doppler spectroscopy is analysing the radial velocity of a star, by observing its movement from our vantage point. While the star does not appear to move from our viewpoint, by using the Doppler effect we can map its actual movement and determine whether it is orbiting around a centre of mass, which indicates the existence of planets(Jones 2008). The Doppler effect means that wavelengths will shift depending on whether the object is moving away or towards us, based on the work by Christian Doppler in 1854. The faster the movement, the larger the shift. If the object is moving towards us, it will have shorter wavelengths (blue shift), if it is moving away, longer wavelengths (red shift). Analysing the absorption lines of the spectrum of a star over a period of time, and whether there is an increase or decrease in the variations of wavelengths, indicates that the star is moving around, or wobbling, and not travelling in a straight line, and thus orbiting a centre of mass (Jones 2008), which indicates the presence of a planet.

By measuring the cyclic variation in the wavelengths, the radial velocity can be calculated. By using the radial velocity and the period in which this change takes place, the minimum mass of the planet can be calculated, as well as the semi-major axis of the planet's orbit. However we also need to know the mass of the star via other methods as a base for these calculations (Jones 2008). Due to the small chance that the planet's orbital plane is aligned vertically to our line of sight, the minimum mass is a fairly good estimate of the planet's mass.

This wobble is extremely small. For example, the Sun will shift via the gravitational influence of the gas giants, Jupiter and Saturn by the small amount of 13 m/s (Marcy & Butler 1998). Earth would

have the even smaller impact of just 0.09 m/s (MobergerWeb). Thus it is easier to discover exoplanets with a greater mass than to detect Earth mass planets.

The main instrument used for taking these measurements is a high resolution cross-dispersed echelle spectrograph, which can be fitted onto existing optical telescopes. For example, HARPS (High Accuracy Radial velocity Planet Searcher), a highly successful exoplanet finder and also discussed in the section "Current Searches", uses a Thorium-Argon lamp to obtain a precision of 1m/s (ESOWeb), which would not be able to detect Earth.

Overview of Exoplanet Search Methods

	Optical Imaging	Transit Photometry	Gravitational Microlensing	Astrometry	Doppler Spectroscopy(Radial Velocity)
Mass of Planet	No ¹	No	Yes	Yes	Minimum Value
Radius of Planet	No ¹	Yes	No	No	No
Semi-major axis of planet	Yes	Calculated From Period	Yes	Yes	Yes
Period of Orbit	Yes	Yes	No	Yes	No
Eccentricity of Orbit	Yes	No	No	Yes	No
Temperature of Planet	Yes	No	No	No	No
Number of planetary systems Discovered	11	105	10	1	290
Multiple Planetary Systems	1	7	1	0	40
Number of Planets Discovered	14	107	11	1	362

¹ If albedo and the atmosphere are known or can be assumed, an estimate can be calculated.

Table 1: A comparison of the various methods of exoplanet discovery. Number of Planets Discovered refers to the number of planets discovered primarily by the method in question. This table refers to current exoplanet candidates. Data taken from <http://www.exoplanet.eu/catalog.php> as of the 30th November 2010.

Overview of Data from Planets Discovered

While there are over 500 exoplanet candidates which have a high probability of being exoplanets, for the purposes of analysing typical attributes of exoplanets, only the 384 exoplanets from the Exoplanet Orbit Database will be used for this analysis. The data from the Exoplanet Orbit Database(ExoplanetOrgWeb) is more complete, and the exoplanets in its catalog have consensus of their existence and attributes from the scientific community, thus allowing for a more detailed analysis. Most of the stars possessing planets are located within a few hundred light years of the Sun (Jones 2008). The cause for this may also be due to the range of most exoplanet searches, however gravitational microlensing can search for exoplanets thousands of light years away. At least 25% of F, G and K main sequence stars within the range of 200 light years of the Sun have

planets (Jones 2008). This indicates that we may be in a region of the Milky Way where most stars similar to that of Sun have planets, but can also be explained by the fact searches are normally targeted towards stars similar to the Sun. Stars that have a high metallicity are also more likely to have planets (Jones 2008). Around 40% of exoplanets orbit their parent star more closely than Mercury orbits the Sun, well outside the Habitable Zone which will be discussed later (Jones 2008). Gravitational microlensing surveys towards the bulge in the Milky Way have found that less than a third of stars have Jupiter sized gas giant masses (Jones 2008). This again indicates that the Solar System is located in the area of the galaxy where stars are more likely to form a planetary system similar to that of the Solar System.

Mass versus Orbital Semi-Major Axis

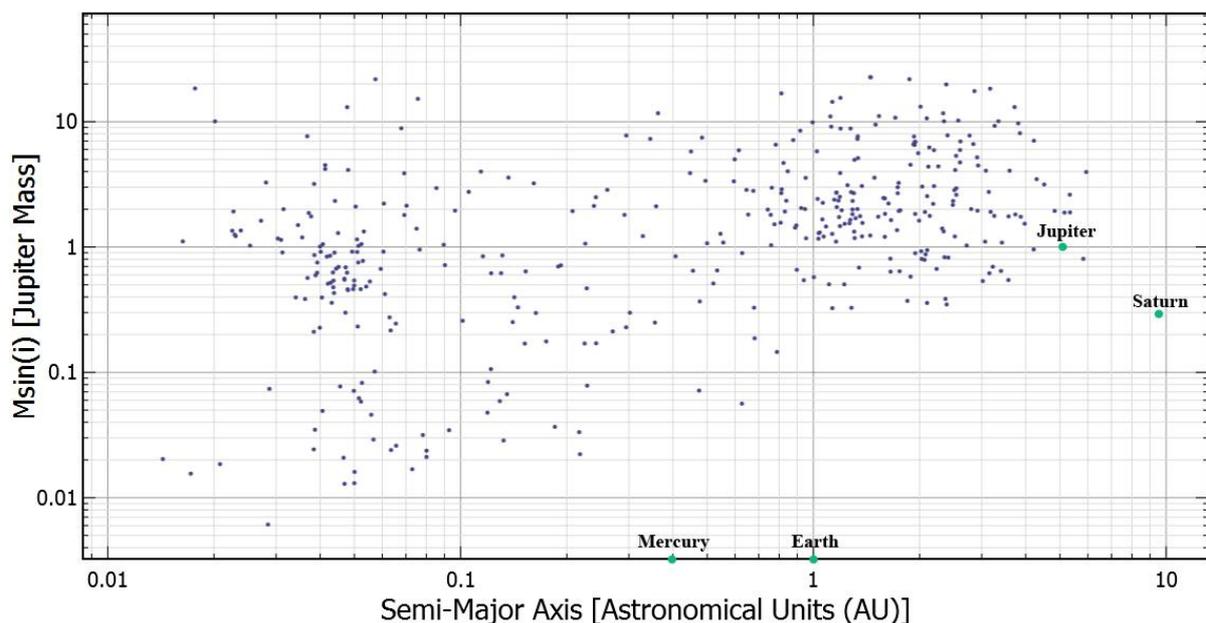


Figure 1: Mass versus Orbital Semi-Major Axis. Mass is the minimum mass as most planets have been discovered using Doppler Spectroscopy. Image taken from <http://exoplanets.org/> as of the 30th of November 2010. Jupiter, Saturn, Earth and Mercury have been added for comparison purposes.

With all the methods used to detect planets around a star the larger the planet is, the easier it is to detect. The average mass of a planet detected is $2.851 M_J$ with the median being $1.457 M_J$. While it is difficult to detect planets with a small mass, it is not impossible. GJ 581 e is the smallest (non-pulsar) planet with the smallest mass discovered so far (Mayor 2009). This planet has a minimum mass of 1.7 times that of Earth. PSR B1257+12A (Konacki & Wolszczan 2003) is another potential candidate for a small planet orbiting a pulsar, but as its mass is approximately $0.020 \pm 0.002 M_{\oplus}$, it would not classify as a planet within our Solar System.

While 81 exoplanets are less than half the mass of Jupiter, 303 exoplanets are at least half the mass of Jupiter or more. As the mass of Jupiter is equal to 318 Earth masses, this is a huge planet in comparison to Earth, which also indicates that most of these planets are gas giants. Planets in the range of 13-80 M_J are more likely to be failed stars, or brown dwarfs rather than planets (Jones 2008).

The majority of planets have a mass between 0.7-5 M_J but, as mentioned previously in the Doppler spectroscopy section, in most cases this is the minimum mass, so Figure 1 may have the masses moving upwards.

The most interesting feature of Figure 1 is how close most planets orbit their parent star. From what we know of gas giant planetary formation, these planets should have formed around 4 AU and have migrated slowly inwards over time (Jones 2008).

Core Accretion versus Disk Instability

There are two main theories on how gas giants form. The first one, known as core accretion, is a bottom up method whereby mass tends to attract other masses, mainly gas, and as more gas is added to the protoplanet, the mass becomes large and possesses more gravity, allowing it to attract more and more gas and other matter (Boss 2009). Once the process is started the mass is thought to rapidly grow. The other theory is disk instability, a top down method of gas giant formation. This is where the disk of matter that is spinning to form the star breaks off into planet sized clumps (Jang-Condell 2007). Gravitational microlensing has found that lower mass stars, such as in the OGLE-2006-BLG-109L system, would not support the core accretion method (Ida & Lin 2005). According to Pasquini et al. (2007) the high metallicity in stars that have a planetary system is because there is more metal in the system that originally formed the stars and planets.

Habitable Zone

The Habitable Zone(HZ) is the range from a star where a planet can support life. This zone also moves with the age of the star, a newly born star generates less light and heat, therefore the HZ is closer to the star. As the star ages and generates more light and heat, the HZ will drift outwards. This means there is an area called the Continuously Habitable Zone, where over the majority of the lifecycle of the star, life can develop and be sustained (Ward & Brownlee 2003).

One of the major goals of discovering exoplanets is attempting to find a rocky planet that exists within the Continuously Habitable Zone, which will increase the possibility of life being discovered.

Gliese 581g is the first terrestrial exoplanet thought to orbit within the HZ. Vogt et al. (2010) discovered a 6th planet in the Gliese system, at a minimum mass of 3.1 M_{Earth} , and orbiting at 0.146 AU with a period of 36.6 days. This would put Gliese 581g right in the middle of the HZ which means it is a potential candidate for support life. However, another team of Astronomers, led by Francesco Pepe have analysed the data from the HARPS (High Accuracy Radial velocity Planet Searcher) and can not confirm the existence of either Gliese 581f and 581g (AstroBioWeb). Thus at present there is no confirmed exoplanet orbiting within the HZ of a star, apart from Earth.

Multiple Planet Systems

As of October 2010 there are over 50 stars with a high probability of multiple planets orbiting them (ExtraSolarWeb). Wright (2009) examined the 30 multiple systems that were discovered prior to August 2008. Wright(2009) found that single exoplanets tended to have a more eccentric orbit than planets in a multiple planetary system. Multiple planets also tended to have a longer orbital distance.

Brief History of Exoplanet Discovery and Important Discoveries

The following section describes a few of the early exoplanet discoveries and will discuss some of the more important discoveries that are not mentioned elsewhere in this report. It is by no means a definitive list, rather it is a highlight of some exoplanet discoveries. Exoplanets have only been confirmed since the early 1990's, thus the field is still relatively new.

In the 1970's, Gordon Walker and Bruce Campbell developed the technique described previous as Doppler spectroscopy in regards to searching for exoplanets (Boss 2009). They spent a total of 12 years, from 1980-1992, searching for exoplanets using the Canada-France-Hawaii Telescope. Although there were a few discoveries suggesting the existence of an exoplanet, there was no firm evidence, and some previously published papers by the pair were even retracted (Boss 2009). However, they did publish a paper in 1988 about the discovery of the exoplanet orbiting the star Gamma Celphi (Campbell, Walker & Yang 1988). For years afterwards there was debate on whether it was a planet or a brown dwarf, but finally, in 2003, it was confirmed to be an exoplanet (Hatzes 2003).

The first exoplanet to be confirmed was in 1992 by Dale Fraile and Aleksander Wolszczan, of two planets orbiting the pulsar PSR B1257+12, with the possibility of a third planet (Wolszczan & Frail 1992) . The third planet was later confirmed (ExtrasolarWeb).

In 1995, using Doppler Spectroscopy, Mayor and Queloz, discovered the first exoplanet orbiting a living star, 51 Pegasi, a planet with a mass half that of Jupiter's, called 51 Pegasi b. This planet has a very short orbital period of 4.2 days, placing it very close to the star, making it almost as hot as the star itself (Boss 2009).

HD 209458 b, a planet in the constellation Pegasus, was the first transiting planet and was discovered in 1999 (Charbonneau et al. 2000). This was important, as at the time 9 other exoplanets had been discovered, and it was theorised that 10% of exoplanets would pass in front of its host star as seen by Earth (Boss 2009). In further studies, the atmosphere of HD 209458 b had been studied, and Barman (2007) believes that water exists in its atmosphere, although a conflicting theory by Richardson (2007) argues that this evidence indicates silicate clouds.

Gliese 436 b is a Neptune sized planet, with a minimum mass of 21 times that of Earth, discovered in 2004 (Butler 2004). What was special about this planet was its relatively low size in comparison to the other exoplanets discovered so far, creating a new class of exoplanet named super-Earths. Previously another super-Earth was discovered, but it orbited a pulsar, not a living star. A super-Earth planet is one with a mass greater than that of Earth, but smaller than that of Jupiter or even Neptune. By this Gliese 436 b was a borderline candidate for a super-Earth, and there has been debate on what type of planet it actually is (Boss 2009).

Gliese 576 d is a planet in the constellation Aquarius that has a mass of approximately 7.5 times that of Earth, and is the first non-arguable super-Earth found (Rivera 2005). The low mass and semi-major orbital radius indicates that it could be terrestrial in nature (Fogg & Nelson 2005).

OGLE 2005-BLG-169-b was a second super-Earth discovered in 2006 (Boss 2009). At this time, half of the four microlensing events had found cold super-Earths, while the other half had found cold Jupiters. This evidence supported the theory that Jean-Phillippe Beaulieu had put forward in 2005 that cold super-Earths are more likely to be found around low mass M-dwarf stars than gas giant planets (Boss 2009). The consensus at the time among the scientific community was that these exoplanets were all formed via the core accretion model, which was also supported by the discovery of failed planets around M dwarfs (Boss 2009).

In 2008, Paul Kalas found the first optical images of an exoplanet from photos taken by Hubble in 2004 and 2006. Fomalhaut b, located in the constellation of Piscis Austrinus, approximately 25 light-years away (HubbleOpticalWeb).

HIP 13044 b is the first planet found that is thought to have originated from outside the Milky Way (NewScientistWeb), as the star HIP 13044 is thought to have been attracted to the Milky Way several billion years ago.

Since the first discovery in the mid 1990's, as of the 30th of November 2010, 504 exoplanet candidates have been discovered (ExtrasolarWeb) with 384 exoplanets achieving consensus in the scientific community (ExoplanetOrgWeb).

Current Exoplanet Searches

There are numerous searches for exoplanets both current and in development, ranging from backyard amateur projects, to projects costing billions of dollars. This section will highlight a few of the more successful current exoplanet searches.

One of the easiest ways to search for exoplanets is by adding a spectrometer to an existing telescope. This method will use Doppler spectroscopy to search for evidence of exoplanets. Two of the more successful spectrometers at discovering exoplanets are the High Accuracy Radial Velocity Planet Searcher (HARPS) and the High Resolution Echelle Spectrometer (HIRES). HARPS has discovered at least 32 new exoplanets since becoming operational in 2003 (HARPSAstroBioWeb). HARPS is located on the European Southern Observatory's 3.6 metre telescope in La Silla, Chile (HARPSWeb).

HIRES is on the W.M Keck Observatory, located in Mauna Kea, Hawaii (HIRESWeb). These are two 10 metre telescopes, which can combine their data using an interferometer for even more improved accuracy (KeckWeb). HIRES has discovered the vast majority of exoplanets since becoming operational in 1996 (Cumming et al. 2008).

The COROT (Convection, Rotation and Planetary Transits) is a space telescope, led by the French Space Agency, the Centre National d'Etudes Spatiales (CNES) (CorotWeb) in collaboration with the European Space Agency (ESA). This telescope was launched in December 2006. COROT has two primary missions, to study the physical structures of stars via stellar seismology (CorotWeb) and to search for exoplanets using transit photometry. Barely 5 months after its launch, in May 2007,

COROT detected its first exoplanet, COROT-Exo-1b located in the constellation Monoceros (COROT-1BWeb). As of the 12th of October 2010, COROT has found at least 16 exoplanet candidates (ExtraSolarCorotWeb). Unfortunately, in 2009 there was a malfunction in a few of the charge coupled devices on COROT, and as a result the telescope's field of view has been reduced by around 50% (COROTEventsWeb). COROT has recently been extended to remain operational until at least the 31st of March 2013 (CorotExtensionWeb).

The Spitzer Space Telescope is an infrared space observatory launched in 2003 (SpitzerWeb). As it is detecting heat radiation, the benefit for exoplanet searches is that it can observe the atmosphere of those planets. Spitzer was the first telescope to directly capture the light of a planet, HD 209458 b (Richardson et al 2007) in 2005. HD 209458 b was also found to have water vapour. Furthermore organic compounds were discovered by combining observations from the Hubble telescope (Barman 2007; SpitzerHD209458bWeb).

The Kepler Mission is the first space based telescope designed solely to search for exoplanets. Kepler's main goal is to find earth size planets within the Habitable Zone (KeplerWeb) using transit photometry. Kepler was launched in March 2009 and is currently scheduled to be operational for at least 3 and half years, but has been designed to be able to remain operational for 6 years (KeplerFaqWeb). A decision will be made on how long to keep Kepler operational, depending on the results gained, but currently Kepler has detected over 700 exoplanet candidates, but these results still need to be analysed to rule out false positives (KeplerDiscoveryWeb), thus it seems highly likely the mission will be extended. Some of these candidates could in fact be two stars orbiting each other. Therefore, to confirm whether the candidates are exoplanets the results are then matched with ground based observations before the exoplanet is confirmed. One of the main advantages of Kepler is that it maintains observations in a 105 degree field of view, containing over 100,000 main sequence stars (KeplerWeb). This means that a planet with an extremely long orbit could be detected by using transit photometry, even if it passes in front of its parent star only once during Kepler's mission. One main way of comparing results is to use Doppler spectroscopy (currently the Keck Telescope with HIRES is primarily used) to check the mass of the object affecting the star (KeplerFopWeb).

Future Exoplanet Searches

While some of the current exoplanet searches will continue for many years, there are projects currently in development that will massively boost the number of exoplanets found, as well as being able to detect much smaller planets, approaching Earth size.

ALMA (Atacama Large Millimetre Array) is one of the largest ground based telescopes to be built, consisting of 66 high precision antennae that will allow it to have an astrometric precision of 100 millionths of an arcsec, which will allow it to detect a Jupiter sized planet out to tens of light years using astrometry (Jones 2008; AlmaWeb). While the size and range may not be as impressive as some of the other searches, this will be the first large scale telescope that is expected to find exoplanets using this method. The resolution of ALMA is so great, it may even be able to directly observe some nearby exoplanets (ALMAExoplanetWeb). ALMA will use wide angle astrometry, being able to use a background star as its base point. Furthermore since ALMA can observe a star

for a 24 hours a day, it is more likely to detect the passage of an exoplanet. ALMA is scheduled to be fully operation by the end of 2012 (ALMAWeb).

The James Webb Space Telescope (JWST) is space based infrared telescope containing a 6.5 metre segmented, unfolding primary mirror, currently being developed, scheduled for launch in 2014 (JWSTWeb). It has 4 main missions, one of which is to study planetary systems and search for the possibility and potential of life in those systems. JWST will have a minimum 5 year mission, which can be extended up to 10 years, depending on the results achieved (JWSTFAQWeb). Unlike the Hubble telescope, JWST will not be serviceable during its mission as it will be located at the second Sun-Earth Lagrange point, around 1.5 million kilometres away from Earth. It will be located there to avoid gravitational issues as the Lagrange point will allow a stable orbit, and also to avoid outside heat interference, complemented with heat shields (JWSTFAQWeb).

NASA is in the very early stages of exploring the technology and science behind Terrestrial Planet Finder Interferometer (TPF-I) (TPFIWeb). This project involves putting multiple telescopes in space, four with one combiner satellite. The satellites would be deployed on the far side of the moon. They will use a technique called nulling interferometry, where the interferometer will adjust the path of the multiple signals to block out a strong source that is interfering with weaker signals (Jones 2008). TPF-I would be able to detect Earth sized planets within a range of tens of light years with a few hours observation. In order to attempt to find a planetary system similar to the Solar System, it would be most useful to target stars where gas giants in a similar orbit to that of Jupiter, or in systems with multiple planetary bodies,. Darwin was a similar project that was under study by the European Space Agency (ESA), but it was ended in 2007 (DarwinWeb).

Conclusion

Although it took almost 2500 years from the first theories regarding the existing of exoplanets until the first confirmed discovery, now almost every week a new exoplanet is discovered. Each new planet helps our understanding of the universe and how the Solar System was created. As technology continues to progress, the rate of discoveries will swiftly increase. In only 20 years, over 500 exoplanets have been discovered. This is a prime example of where the theory was sound, but technology had not caught up, but now that it has, the future with the Kepler and James Webb Space Telescope for example, promises to yield many exoplanet discoveries. The rapid pace of discoveries, and major recent discoveries as HIP 13044 b (the exoplanet from another galaxy) and the arguable Habitable Zone planet Gliese 581g, have helped capture the general public's imagination, which may hopefully lead to even more funding for exoplanet research.

One of the main prizes in exoplanet searches is an Earth sized planet, within the Habitable Zone of the star. Hopefully within infrared telescope range, where water and other organic chemicals could be detected in its atmosphere. As technology continues to develop, the mass of the exoplanets able to be detected will decrease, approaching Earth mass and hopefully even lower, while at the same time the range will be increased. The field of exoplanets is still relatively young and the next few decades are going to produce some amazing results as both the field, technology and methods improve and grow.

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